

***d-d* Elastic Scattering at 10.5 Mev\***

LOUIS ROSEN AND J. C. ALLRED

*University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

(Received July 16, 1952)

Deuterons from the 42-inch cyclotron were scattered by a thin deuterium gas target. Scattered particles were detected by photographic emulsions in a nuclear multiplate camera. The differential cross section for elastic scattering was measured at  $5^\circ$  intervals in the center-of-mass system, from  $25^\circ$  to  $145^\circ$ , the estimated absolute rms standard error of the measured cross sections being  $\pm 3.1$  percent. The measurements extend the angular range of the previous measurements of Allred, Erickson, Fowler, and Stovall at 10.8 Mev, and are in very good agreement with their values when the difference in bombarding energy is taken into account.

**I. INTRODUCTION**

THE *d-d* interaction has long been a subject of experimental and theoretical study, since the small number of nucleons involved and the identity of the particles simplify somewhat the possible modes of interaction and make the mathematical treatment of this problem feasible. In the energy region of the present measurements, the differential cross section for *d-d* elastic scattering has been measured previously at this laboratory by a technique in which a proportional counter detected deuterons scattered by a thin deuterium gas target, the incident deuteron energy being 10.8 Mev.<sup>1</sup> Exploratory measurements were also made<sup>2</sup> in which the proportional counter was replaced by a small camera containing a single nuclear emulsion plate. In this paper, the results of measurements made with a nuclear multiplate camera<sup>3</sup> are reported. These results extend the angular range of the previous measurements and are in essential agreement with them, when the difference in energy is taken into account.

Initially, the purpose of this experiment was to serve as a check on the properties of the rare gas target of the previous paper,<sup>4</sup> as well as on the newer mounting of the Faraday cup at the back of the camera. In the course of that investigation, runs were made in which deuterium gas was contained within a rare gas target chamber which was centrally located in the evacuated camera. Another set of data was taken with the gas target chamber absent and the whole camera filled with gas. Preliminary analysis of these data indicated that the data taken without the rare gas target in position could extend the angular range of the previous differential cross section measurements on *d-d* scattering. The following investigation was conducted without the gas target chamber.

**II. EXPERIMENTAL PROCEDURE**

The instrumentation of the cyclotron,<sup>5</sup> the use of the nuclear multiplate camera, and the analysis of the

\* Work performed under the auspices of the AEC.

<sup>1</sup> Allred, Erickson, Fowler, and Stovall, *Phys. Rev.* **76**, 1430 (1949).

<sup>2</sup> Rosen, Tallmadge, and Williams, *Phys. Rev.* **76**, 1283 (1949).

<sup>3</sup> Allred, Rosen, Tallmadge, and Williams, *Rev. Sci. Instr.* **22**, 191 (1951).

<sup>4</sup> Allred, Armstrong, Hudson, Potter, Robinson, Rosen, and Stovall, Jr., *Phys. Rev.* **88**, 425 (1952).

<sup>5</sup> Curtis, Fowler, and Rosen, *Rev. Sci. Instr.* **20**, 388 (1949).

plates were the same as in the previous paper.<sup>4</sup> Similar techniques have been fully described elsewhere.<sup>6</sup>

Runs were made at pressures from 0.8 to 10.1 cm Hg, at accurately measured temperatures in the range  $20^\circ$  to  $25^\circ\text{C}$ , with integrated deuteron currents in the range 3.0 to 20.5  $\mu\text{coulomb}$ . The target gas contained 99.5 percent deuterium and 0.5 percent hydrogen, according to the manufacturer's specifications. This analysis was confirmed by the observed number of proton tracks in the distributions of range *versus* number for the scattered particles. Reference 2 indicates the method which we used for analysis of gas impurities from the scattering data.

A total of 124,000 tracks were counted, about 2200 tracks per plate analyzed. The incident beam energy was  $10.5 \pm 0.15$  Mev as determined by the method of reference 2.

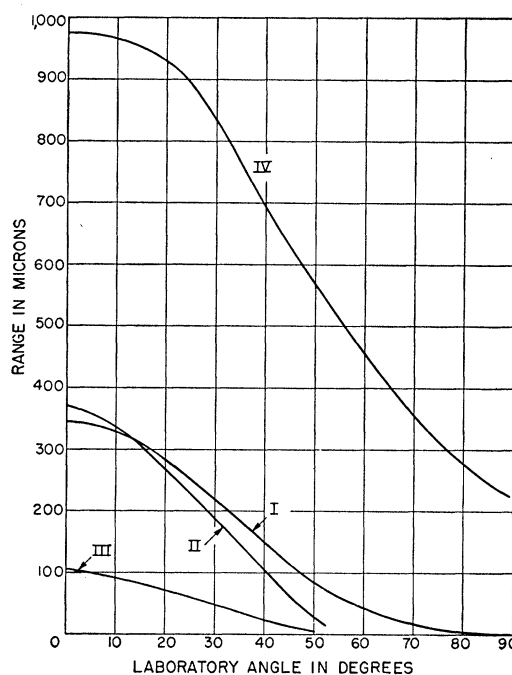


FIG. 1. Variation of range with angle for the products of the *d-d* interaction: I. elastically scattered deuterons; II. tritons from  $D(d,p)T$ ; III.  $\text{He}^3$  from  $D(d,n)\text{He}^3$ ; IV. protons from  $D(d,p)T$ .

<sup>6</sup> L. Rosen and J. C. Allred, *Phys. Rev.* **82**, 777 (1951).

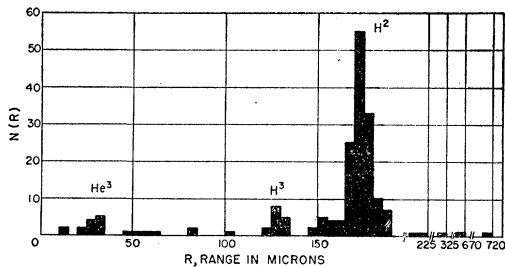


FIG. 2. Range distribution of  $d$ - $d$  interaction products at  $37.5^\circ$  in the laboratory system, 181 tracks.

### III. ANALYSIS OF DATA; RESULTS

Figure 1 shows the distribution in range of the scattered deuterons as a function of laboratory angle, together with the ranges of the protons, tritons, and  $\text{He}^3$  particles from the reactions  $\text{D}(d,p)\text{T}$  and  $\text{D}(d,n)\text{He}^3$ . It is seen that in the angular range from  $5^\circ$  to  $25^\circ$  in the laboratory system, the tritons may add counts to the deuteron peak since, in our experiment, it was not possible to observe the differences in specific ionization. In this region, where the two peaks overlap, the triton contribution was subtracted on the basis of the pre-

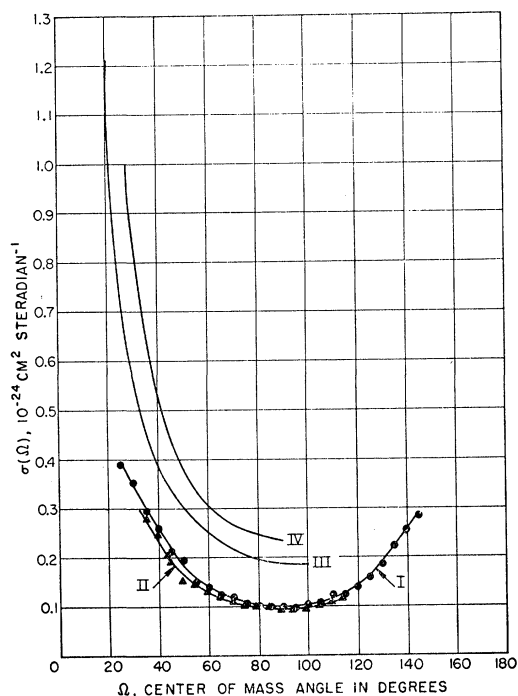


FIG. 3. Differential cross section for  $d$ - $d$  scattering as a function of center-of-mass angle: I. Present data,  $E_D=10.5$  Mev; II. Allred, Erickson, Fowler, and Stovall,  $E_D=10.8$  Mev; III and IV. Blair, Freier, Lampi, Sleanor, and Williams,  $E_D=3.50$  and  $2.01$  Mev, respectively.

viously measured  $\text{D}(d,p)\text{T}$  differential cross section at this bombarding energy.<sup>7</sup>

Figure 2 shows a typical range distribution for the scattered and reaction particles. These particles were observed at  $37.5^\circ$ , an angle at which the triton peak is resolved. The deuteron peak, between  $150$  and  $200 \mu$ , determines the number of deuterons scattered within the solid angle defined by the slit system geometry and the total width of the swaths read on each plate.

Figure 3 and Table I give the measured differential cross section as a function of center-of-mass angle. As is to be expected from the identity of the particles, the differential cross section is symmetrical about  $90^\circ$ . Figure 3 also shows the previous data at  $10.8$  Mev of Allred *et al.*<sup>1</sup> and a portion of the lower energy angular distributions measured by Blair *et al.*<sup>8</sup> The measurements at  $10.8$  and  $10.5$  Mev are in good agreement with the results of Burrows, Gibson, and Rotblat<sup>9</sup> at  $8$  Mev.

The estimated absolute rms standard error of the cross sections of Table I is  $\pm 3.1$  percent, apportioned as

TABLE I. Measured differential cross sections,  $\sigma(\Omega)$ , in  $10^{-24}$   $\text{cm}^2/\text{steradian}$  as a function of center-of-mass angle,  $\Omega$ , in degrees.

$\Omega$	$\sigma(\Omega)$	$\Omega$	$\sigma(\Omega)$
25	$0.389 \pm 0.012$	90	$0.100 \pm 0.003$
30	$0.354 \pm 0.011$	95	$0.097 \pm 0.003$
35	$0.295 \pm 0.009$	100	$0.104 \pm 0.003$
40	$0.263 \pm 0.008$	105	$0.109 \pm 0.003$
45	$0.213 \pm 0.007$	110	$0.123 \pm 0.004$
50	$0.197 \pm 0.006$	115	$0.124 \pm 0.004$
55	$0.152 \pm 0.005$	120	$0.140 \pm 0.004$
60	$0.143 \pm 0.004$	125	$0.162 \pm 0.005$
65	$0.128 \pm 0.004$	130	$0.185 \pm 0.005$
70	$0.122 \pm 0.004$	135	$0.221 \pm 0.007$
75	$0.107 \pm 0.003$	140	$0.253 \pm 0.008$
80	$0.102 \pm 0.003$	145	$0.287 \pm 0.009$
85	$0.101 \pm 0.003$		

follows: counting statistics,  $\pm 2.2$  percent; current integration,  $\pm 1.7$  percent; measurement of gas pressure and temperature,  $\pm 0.5$  percent; geometrical factors,  $\pm 1.0$  percent; and errors due to microscope calibration and personal factors,  $\pm 1.0$  percent. Among the cross sections measured in six runs, the mean deviation was calculated at angles which were duplicated in two or more runs. The standard error derived from this calculation was 2.3 percent, a measure of the internal consistency of the data.

The authors wish to thank Dr. J. L. Fowler and members of the cyclotron group for their valuable aid in the experiments of this and the previous paper. For the analysis of the plates, we are indebted to the staff of the nuclear plate group.

<sup>7</sup> Allred, Phillips, and Rosen, *Phys. Rev.* **82**, 782 (1951).

<sup>8</sup> Blair, Freier, Lampi, Sleanor, and Williams, *Phys. Rev.* **74**, 1594 (1948).

<sup>9</sup> Burrows, Gibson, and Rotblat, *Proc. Roy. Soc. (London)* **A209**, 489 (1951).